Superconducting Nanowire Single Photon Detectors for Deep Space Optical Communication

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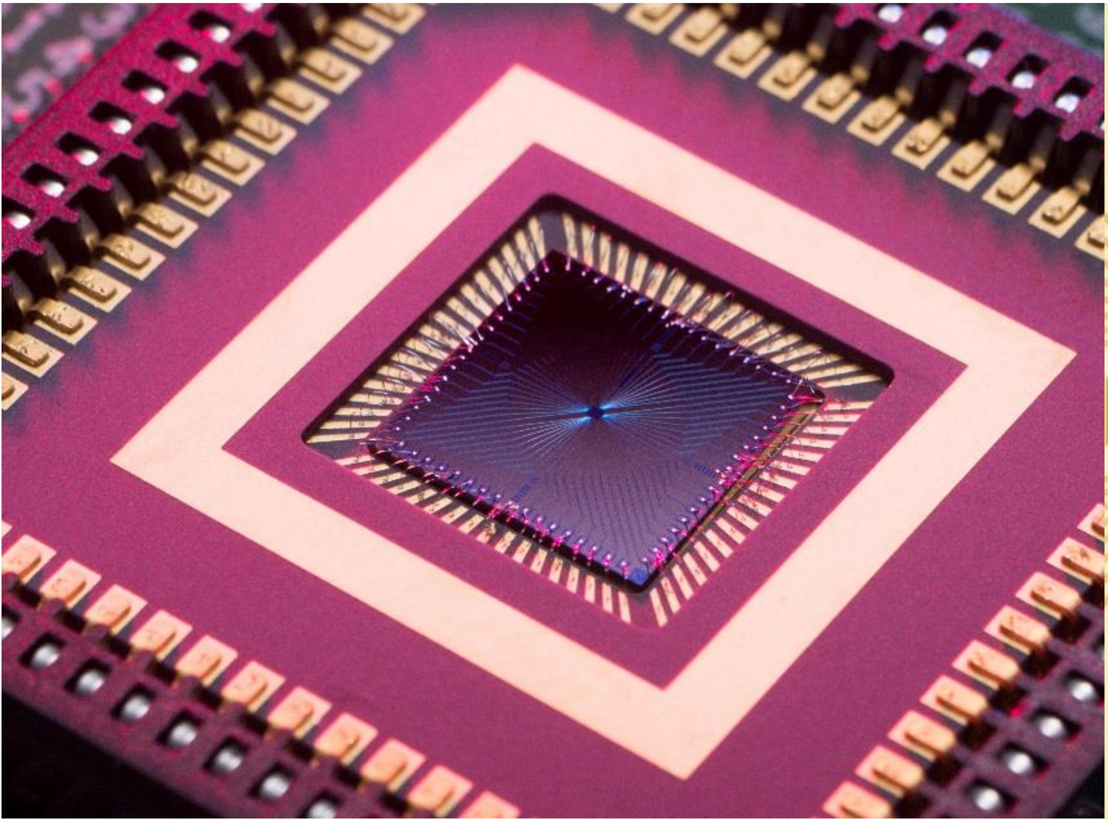
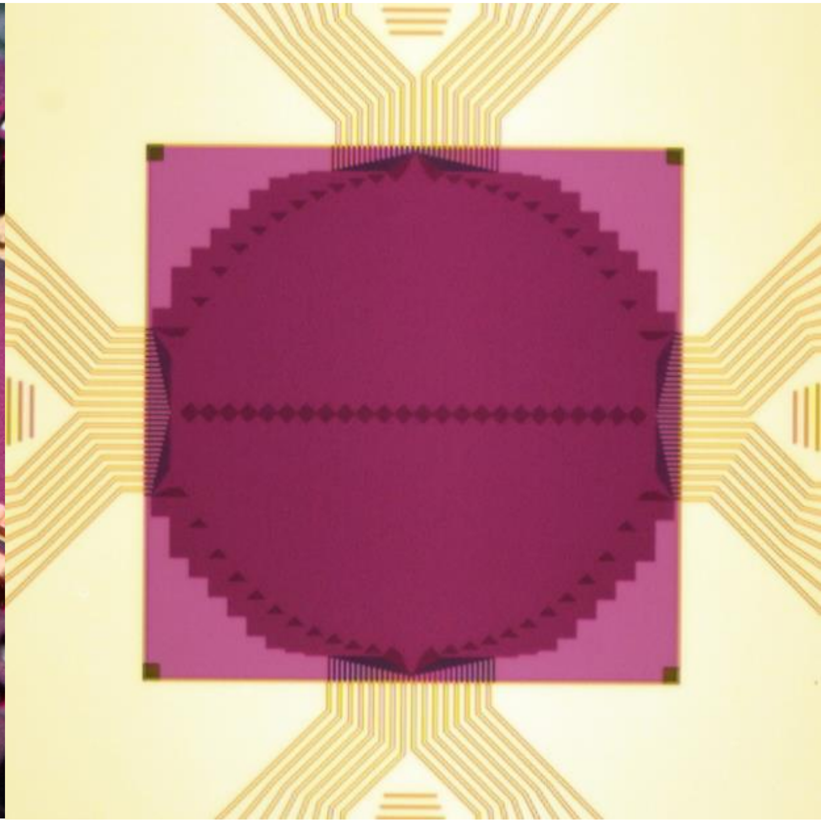

JPL SNSPD Development Team

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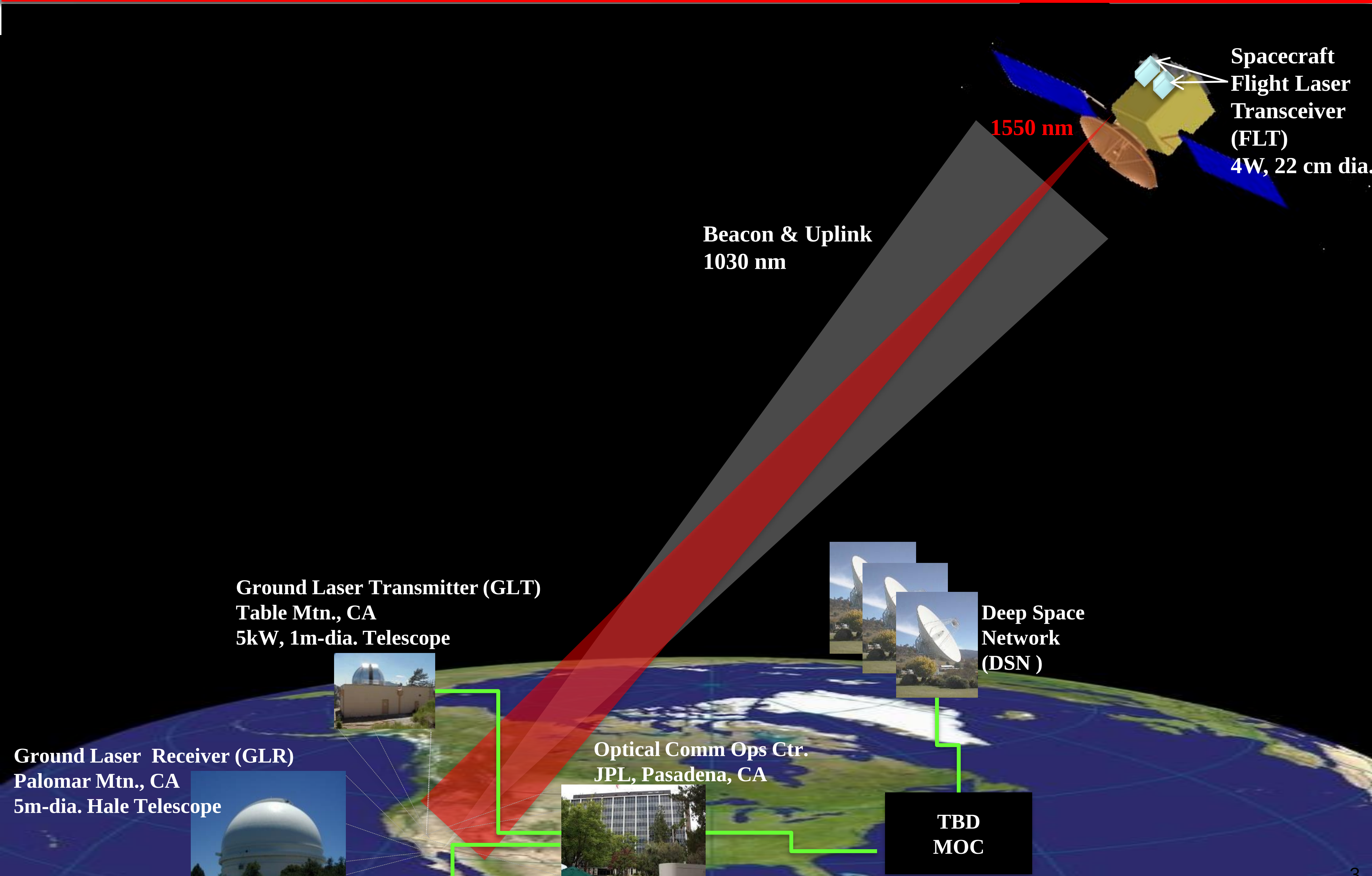
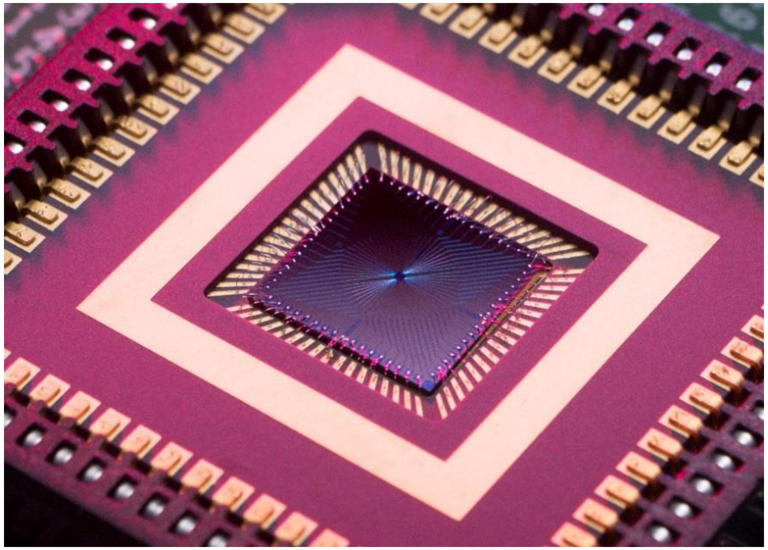
DSOC Project Overview



DSOC Project Overview

- Phase A of NASA Technology Demonstration Mission
- Ground system funded by NASA SCaN
- Flight terminal planned to launch on PSYCHE spacecraft in 2023
- Projected downlink data rates from 200 kbps - 265 Mbps
- Developing a 320-µm 64-pixel WSi SNSPD array for the ground receiver



DSOC Project Systems

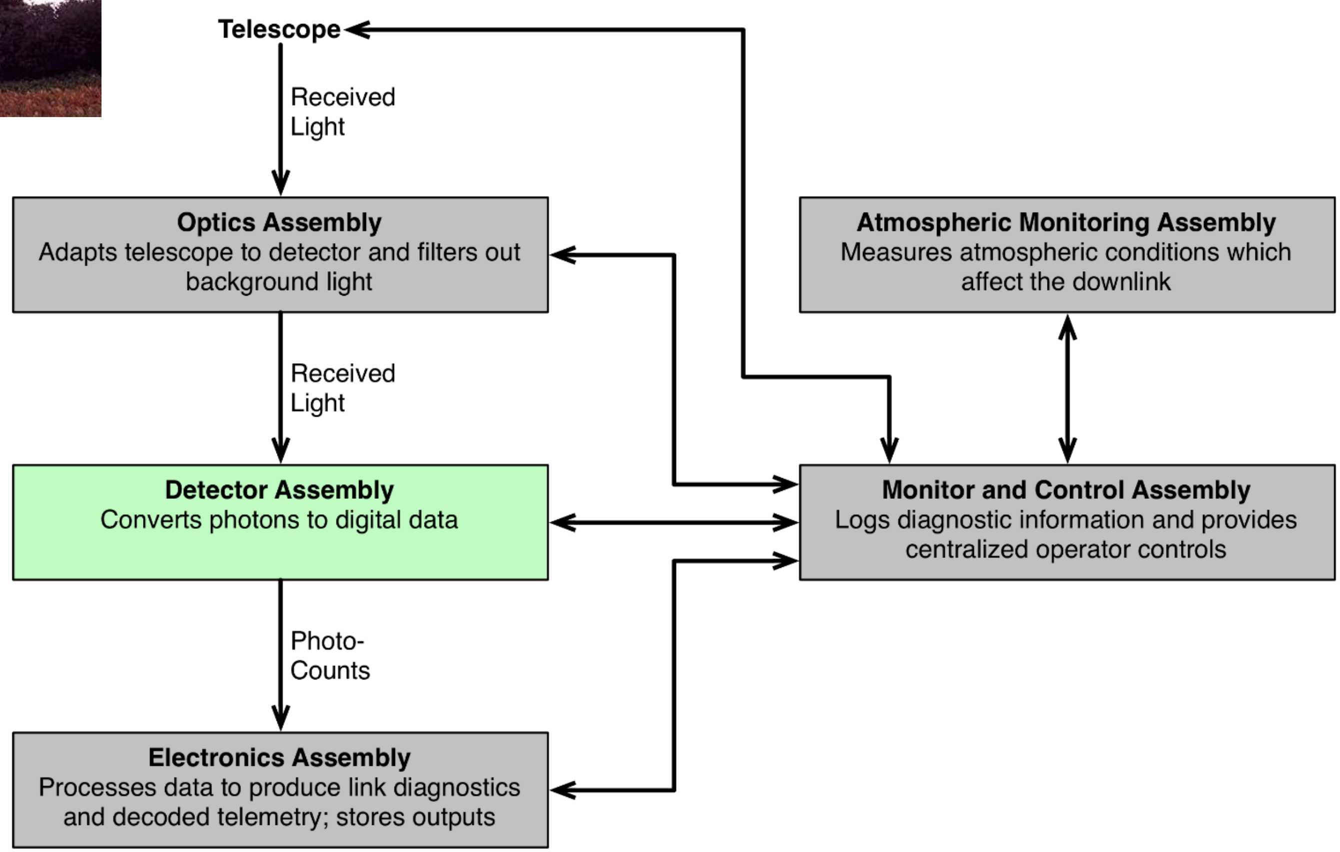
Flight Laser Terminal (FLT)

Ground Laser Transmitter (GLT)
OCTL, Table Mountain CA

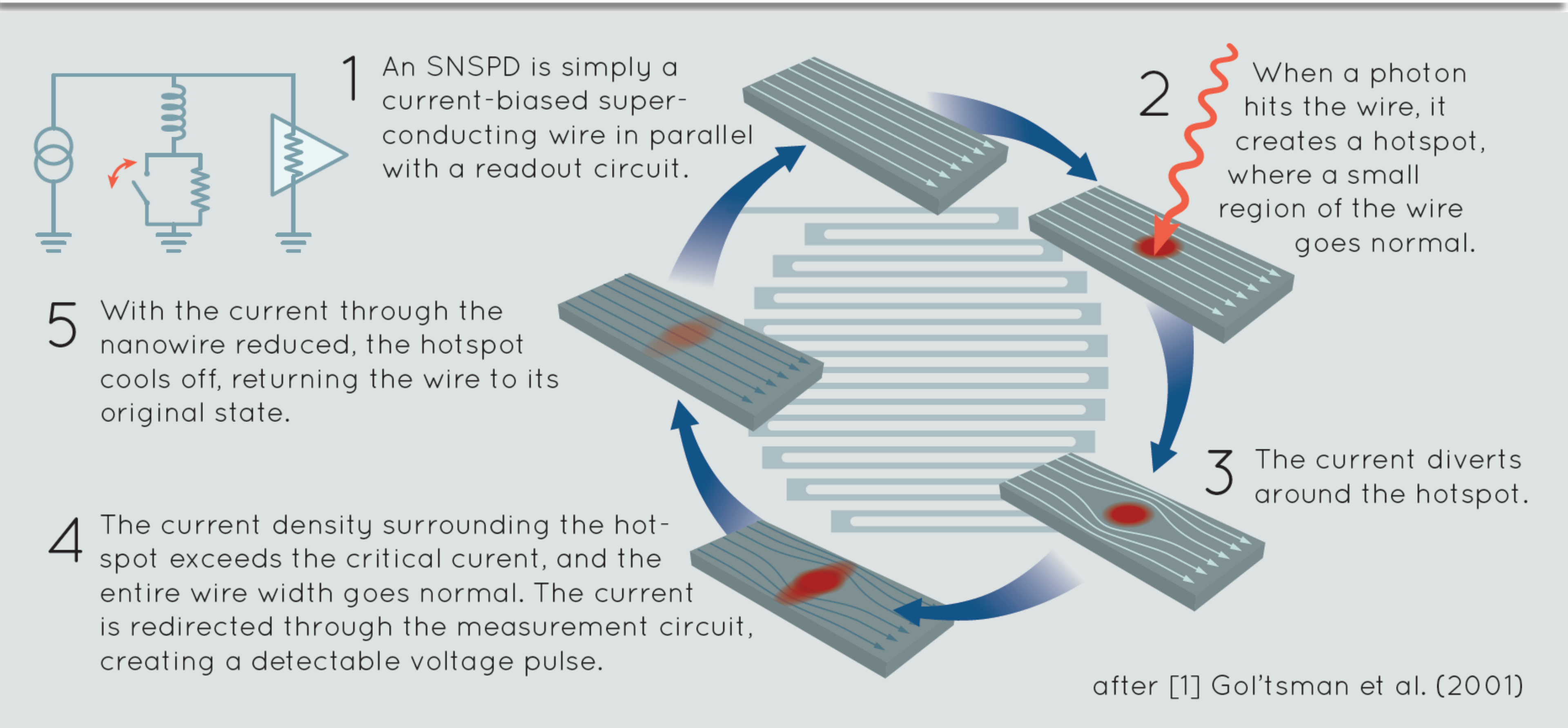
Ground Laser Receiver (GLR)
Hale 200-inch, Palomar CA

Mission Operation Center (MOC)
JPL

Ground Laser Receiver Assemblies

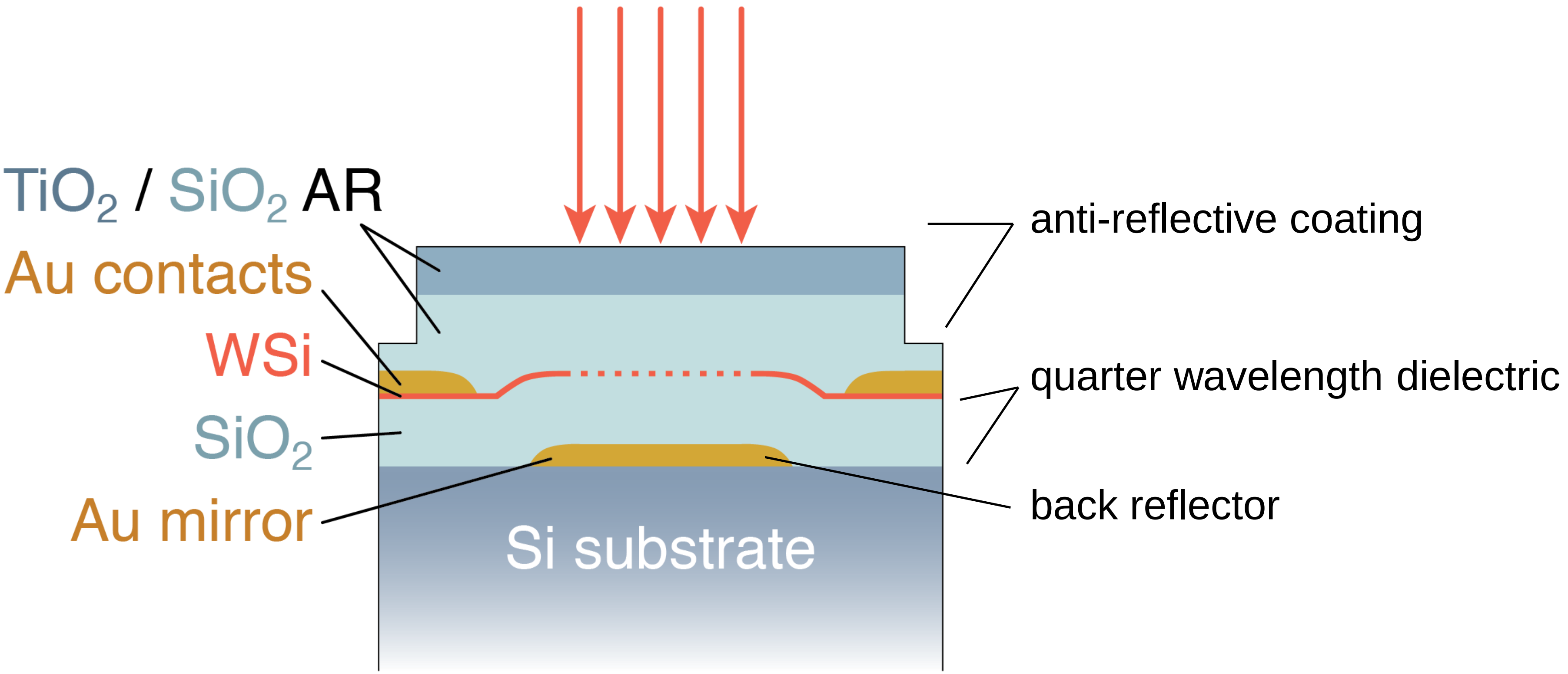


SNSPD Device Concept



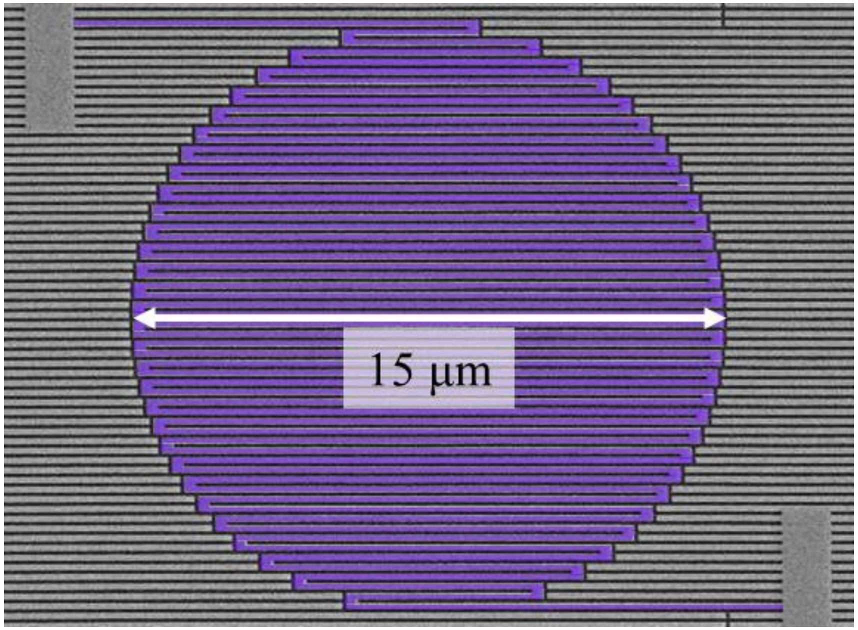
- Performance exceeds conventional detectors but requires cryogenic cooling (1-3 K)
- 15 years of active development (MIT / LL, NIST, JPL, Russia, Europe, Japan, China)
- Key challenge for deep-space optical communication has been limited active area

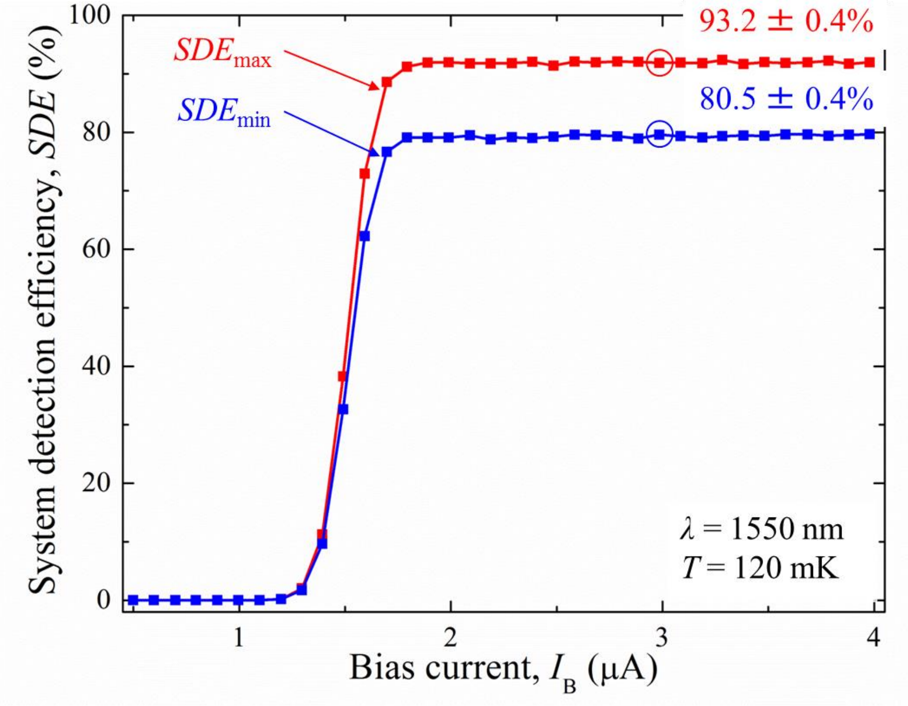
Optical Cavity to Enhance Absorption



- Photosensitive nanowire element is embedded in a vertical quarter-wave cavity
- Enhances detection efficiency from 20% to >90%

Single-Pixel WSi SNSPDs

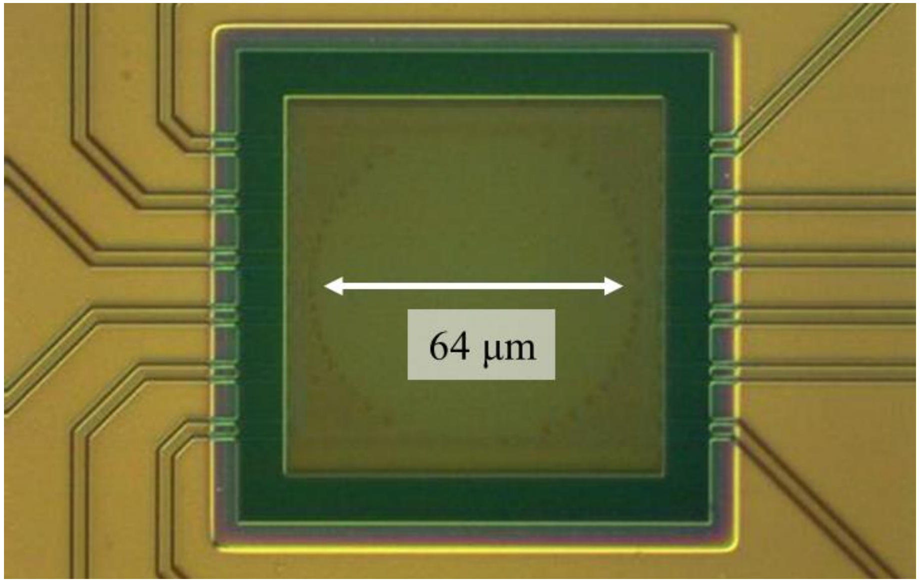


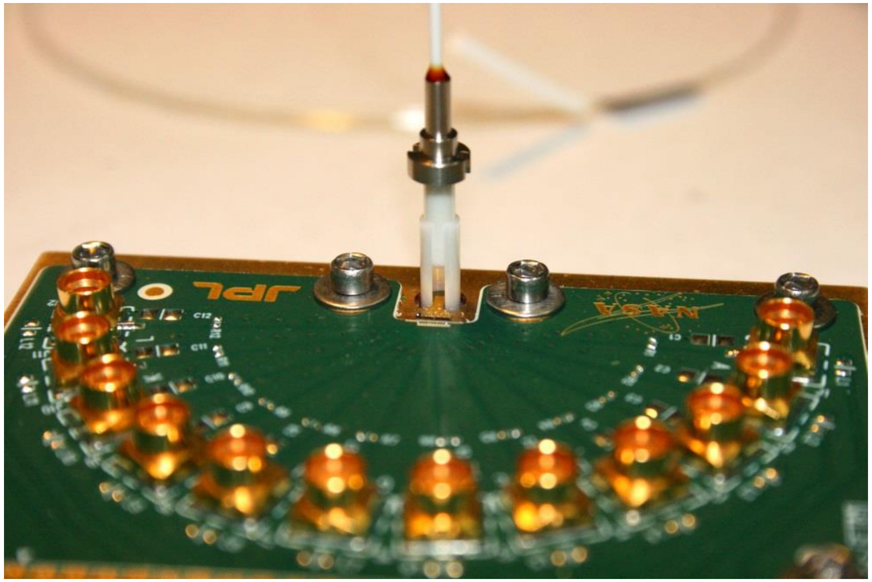


Marsili et al, *Nature Photonics* (2013)

- 2012 collaboration between JPL and NIST
- Record 93% system detection efficiency at 1550 nm
- Amorphous WSi material system enables large active-area arrays

12-pixel WSi SNSPDs for LLCD

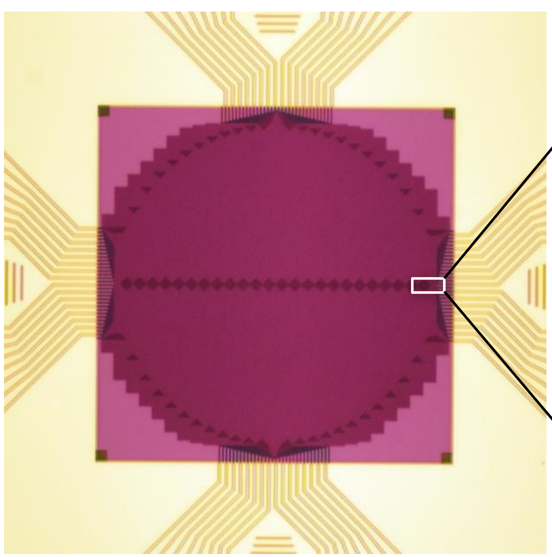




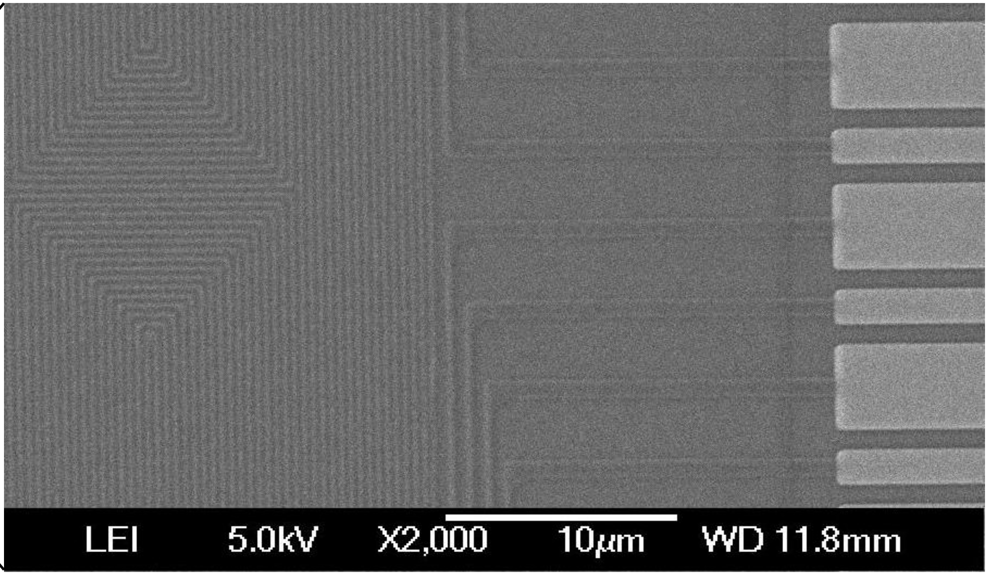
- 12-pixel WSi SNSPD array with 64 µm diameter active area
- Fielded in a secondary ground station for LLCD, 77 Mbps downlink
- Self-aligned cryogenic fiber coupling to 1-meter telescope
- 780 mK cryostat

64-pixel WSi SNSPD Array for DSOC

- 64-pixel WSi SNSPD array embedded in optical cavity optimized for 1550 nm
- 320-µm dia. free-space coupled active area, 4 quadrants, 16 co-wound wires per quadrant
- 10% nanowire fill factor: 4.5 x 160 nm wires on a 1.6 µm pitch
- Two-layer AR coating to enhance efficiency at low fill factor: theoretical 77% device efficiency
- 43% efficiency measured on a single quadrant, 63 out of 64 measured nanowires plateau
- Work to improve the efficiency is currently underway
- Currently working on a full 64-channel readout system



64-pixel WSi SNSPD array with 320-µm active area



SEM image of 64-pixel 320-µm array

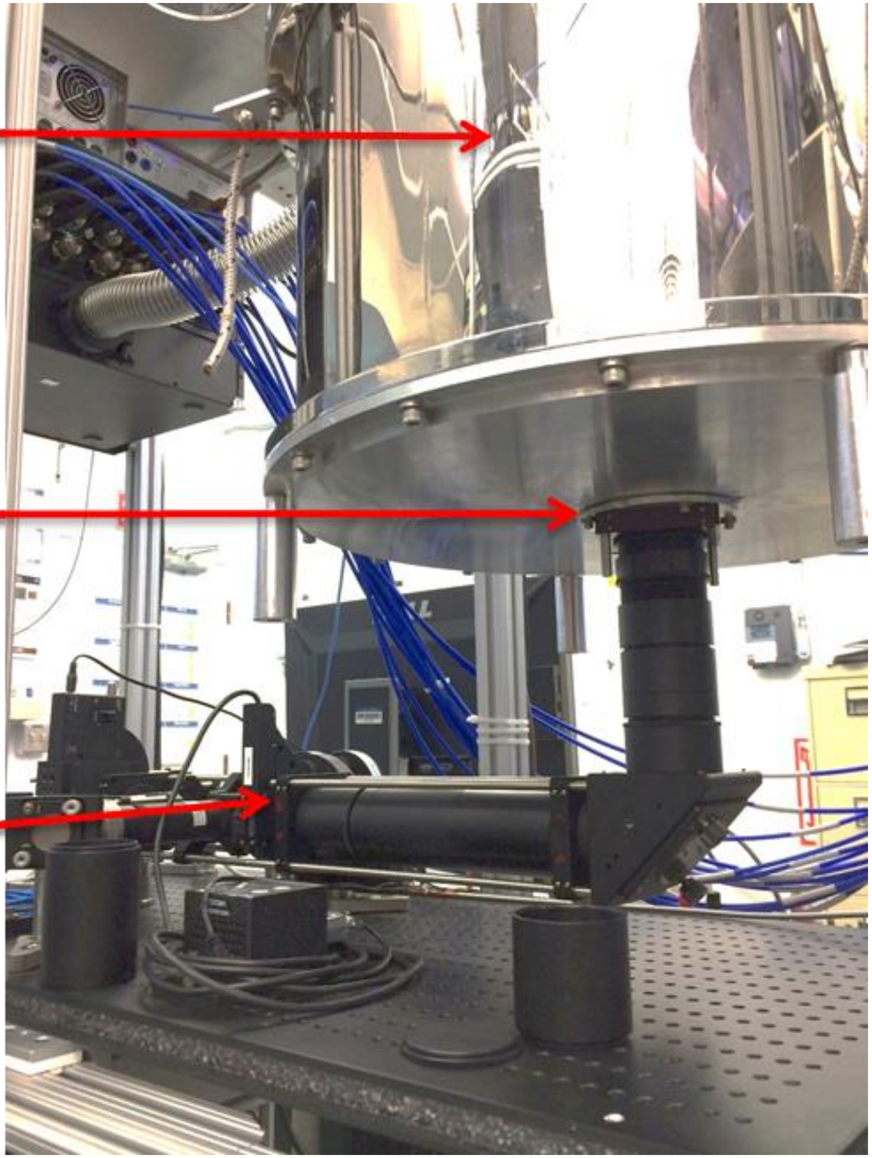
Free Space Coupling

- Efficient coupling to large apertures requires free space coupling
- Previous demos have all used fiber
- 300 K vacuum window
- 40 K, 4 K IR filters to block thermal background
- Engineering tradeoff between efficiency and false counts
- Must consider finite numerical aperture of detector

Cryostat

Cryostat window

Free space optical system



Project Goals and SNSPD Performance

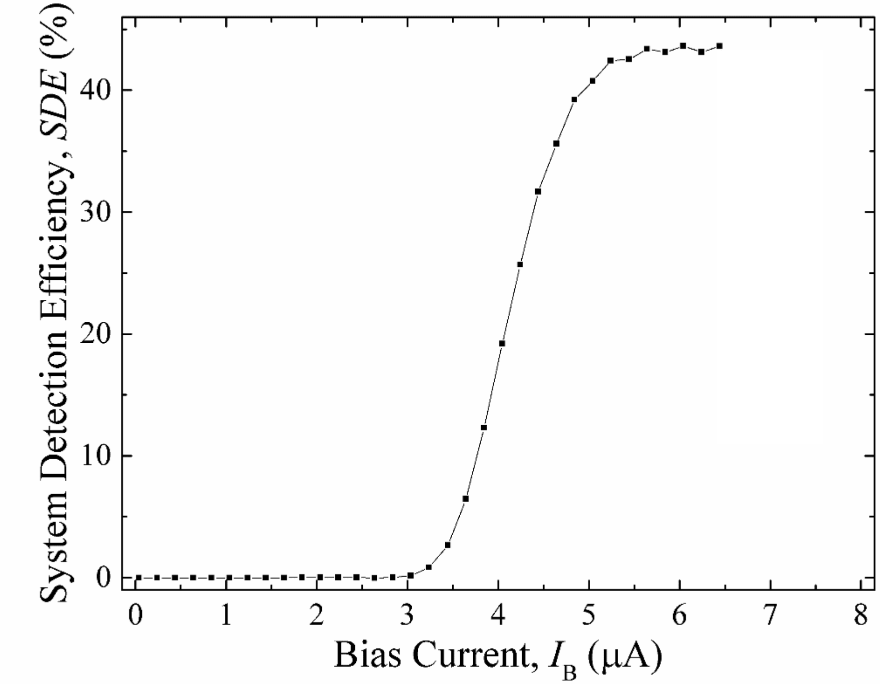
	DSOC Goals	Progress to date	Capability Acheived
Detection Efficiency	>50% minimum >70% desired	93% (fiber-coupled single pixel) 43% (Free Space, 320 μm array)	✓
Timing Jitter	100 ps (1-sigma)	50 - 70 ps (1-sigma) (not including TDC)	✓
False Counts	< 10 kcps / pixel free space coupled	< 7 kcps / pixel (320 μm array)	✓
Maximum Count Rate	830 Mcps (264 Mbps, 0.2 AU, night cruise)	1.26 Gcps (20 Mcps / pixel, 63 pixels)	✓
Active Area	260 μm diameter (35 μrad seeing, Palomar daytime)	320 μm diameter (50 μrad seeing, Palomar daytime)	✓
Numerical Aperture	f/1.2	f/4	

1550 nm operating wavelength

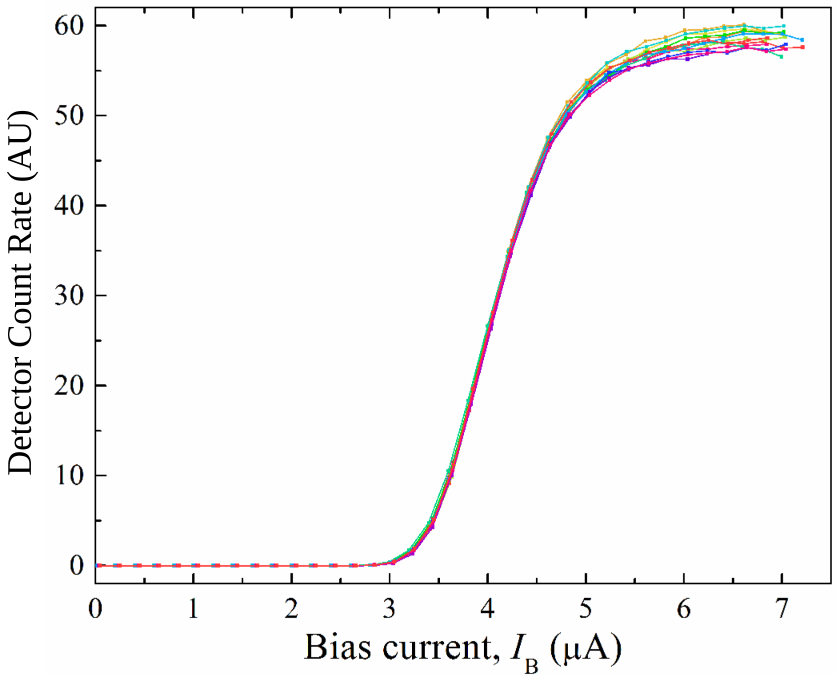
Free space coupled

1 K operating temperature

Efficiency Measurements



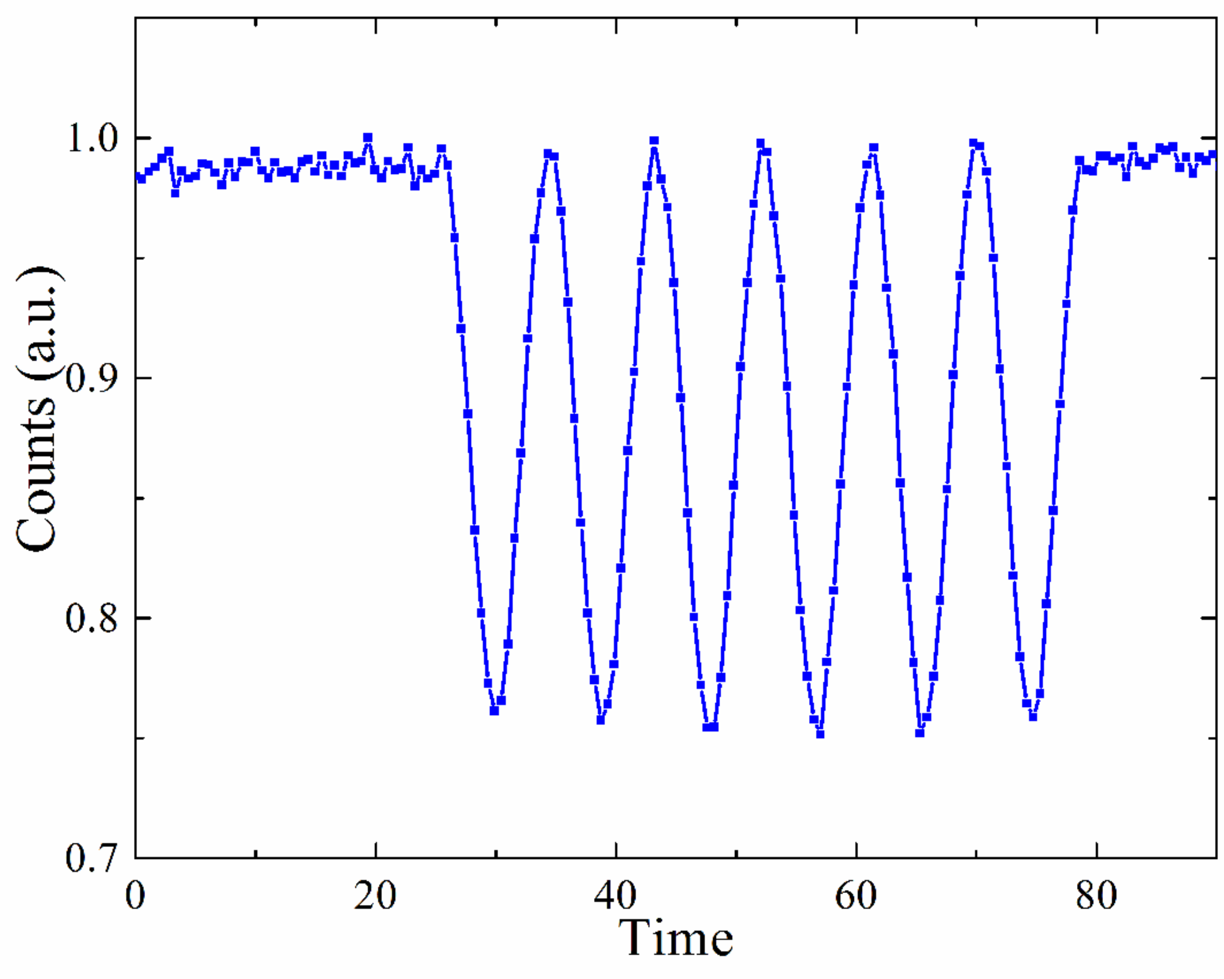
Sum of 16 detection efficiency curves in one quadrant



Individual count rate curves superimposed

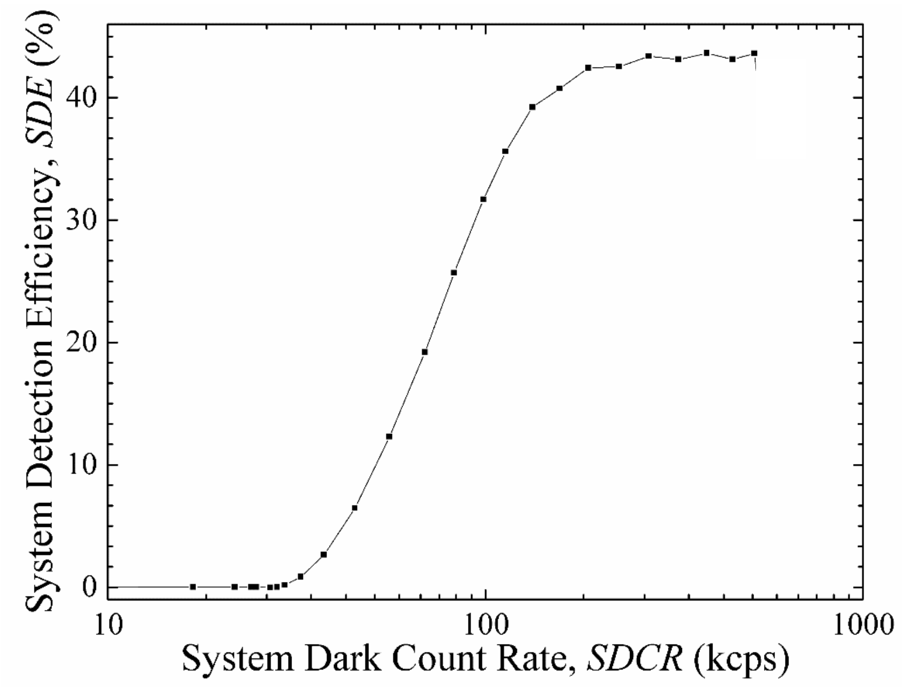
- System detection efficiency measured through cryostat window, 40K and 4K IR filters
- Measured SDE by focusing entire spot into one array quadrant (16 channels)
- Measured 43% efficiency in TE polarization at 1550 nm, theory predicts 77%
- Suspect that on-chip cavity is not properly centered at 1550 nm

Polarization Dependence of Efficiency

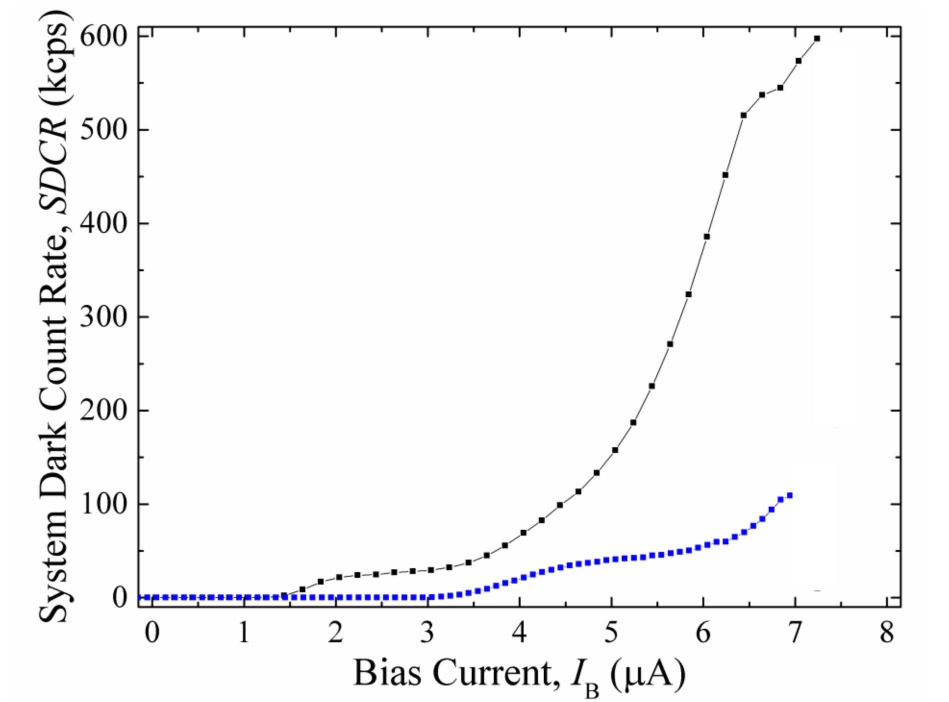


- 25% variation between TE and TM polarizations
- RCWA theory predicts only 18% variation between polarizations

False Count Rate



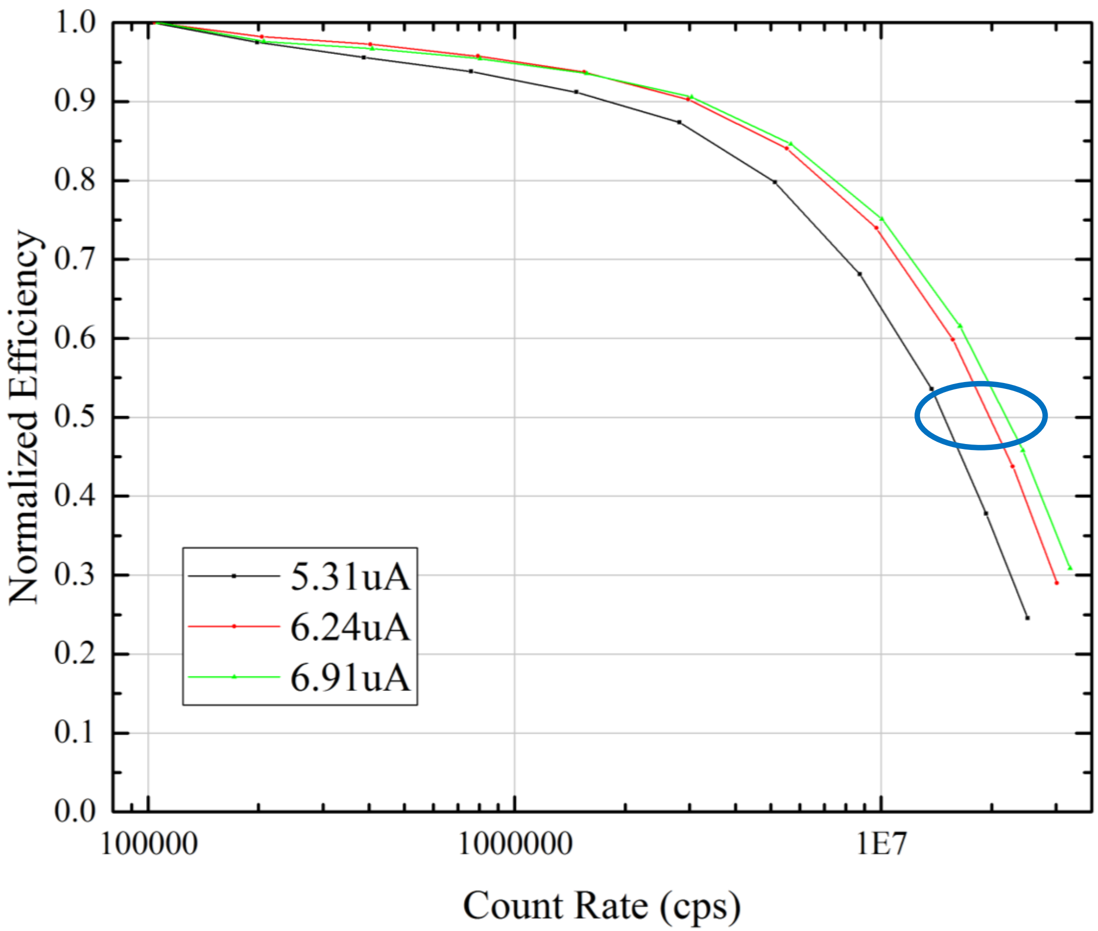
Efficiency vs Dark Count Rate for sum of 16 pixels in quadrant BK7 Glass Filter



Comparison of DCR with plastic (blue) and BK7 (black) filters

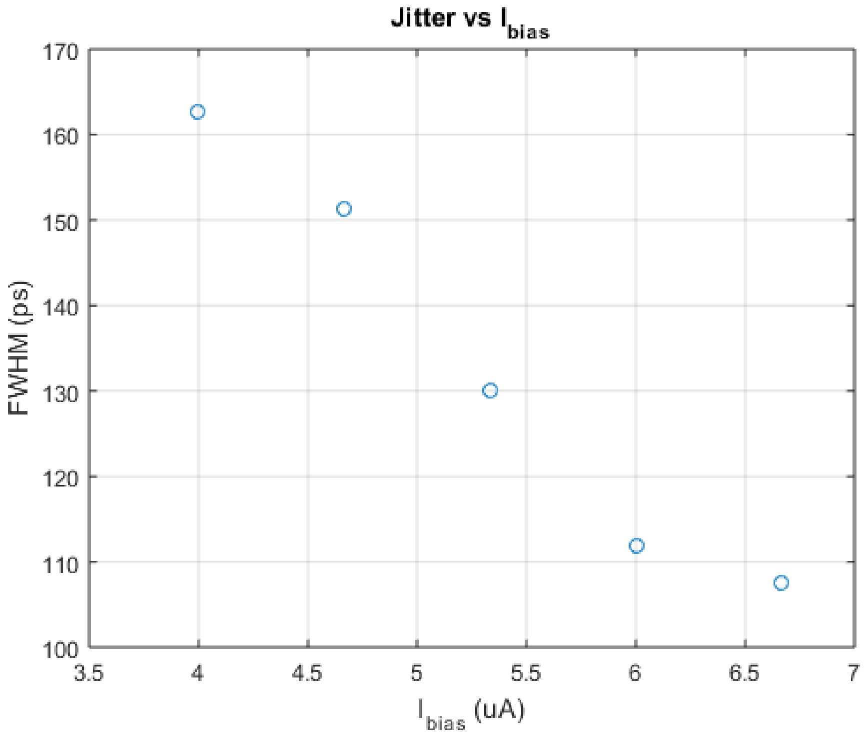
- False counts are strictly limited by thermal IR backgrounds (< mHz intrinsic dark rates)
- 1 – 7 kcps per pixel with cryogenic plastic IR filters (not AR coated, 40% SDE)
- 4 – 30 kcps per pixel with BK7 glass filters (43% SDE)
- < 10 kcps per pixel required for DSOC

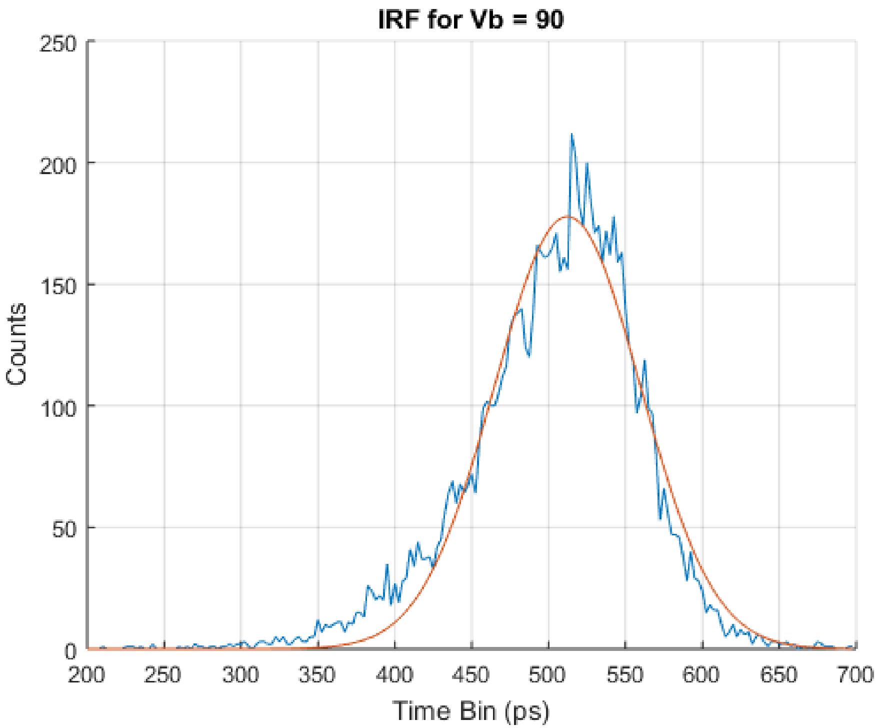
Maximum Count Rate



- 3dB MCR of 15 Mcps at the back of the plateau, 22 Mcps at the front
- DC coupled cryogenic amplifier chain (commercial components)
- For 63 working pixels, this gives an array MCR of 900 Mcps at the back, 1.3 Gcps at the front

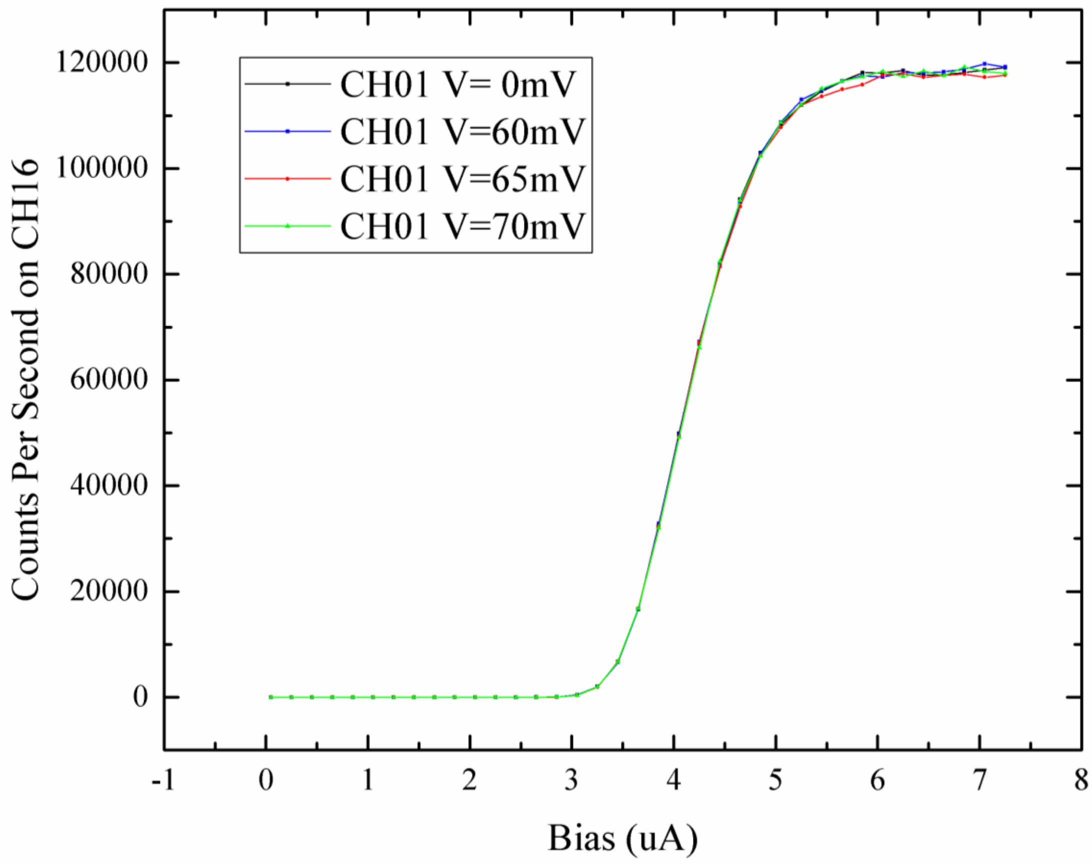
Timing Jitter through Cryoamps





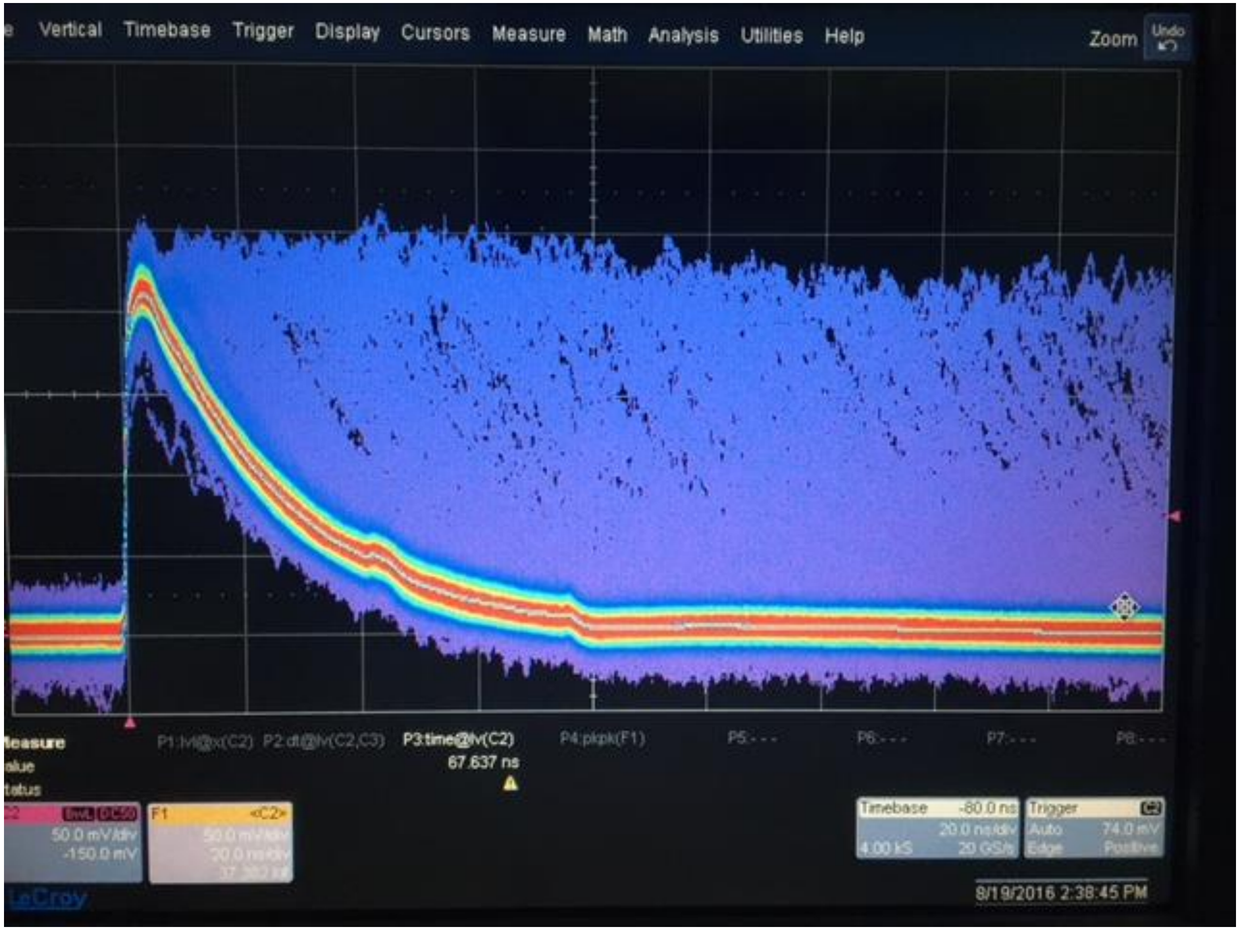
- Timing jitter 50 – 70 ps FWHM across the plateau
- Easily meets DSOC project goals of 100 ps 1-sigma
- Measured through DC coupled cryogenic amplifier
- Scaling suggests that readout SNR is the dominant jitter mechanism

No Crosstalk



- No crosstalk is observed with 10% nanowire fill factor co-wound arrays
- Severe crosstalk was observed with 20-40% fill factor co-wound arrays
- From scaling, crosstalk is believed to be thermal
- Physics of crosstalk is under study with a generalized electrothermal model

No Measurable Afterpulsing

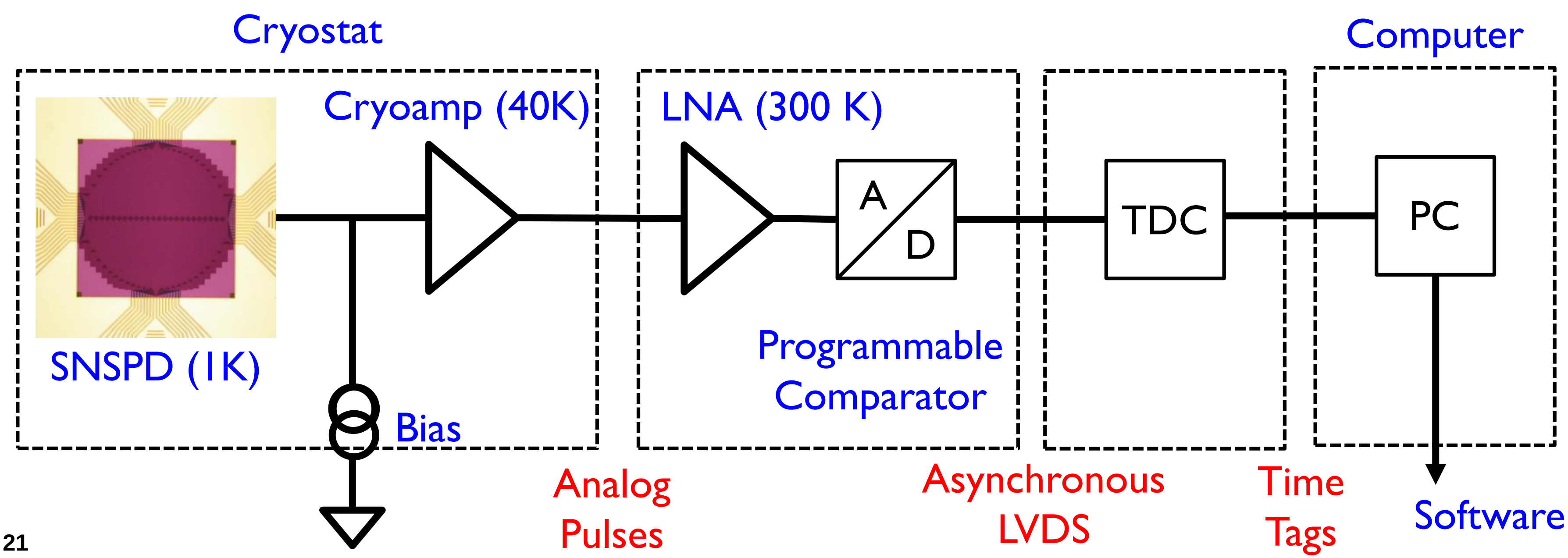


- No afterpulsing is observable from persistence traces (shown) or interarrival time histogram
- Some latching effects are seen at the highest bias currents, but not enough to impact MCR

SNSPD Array Readout Concept

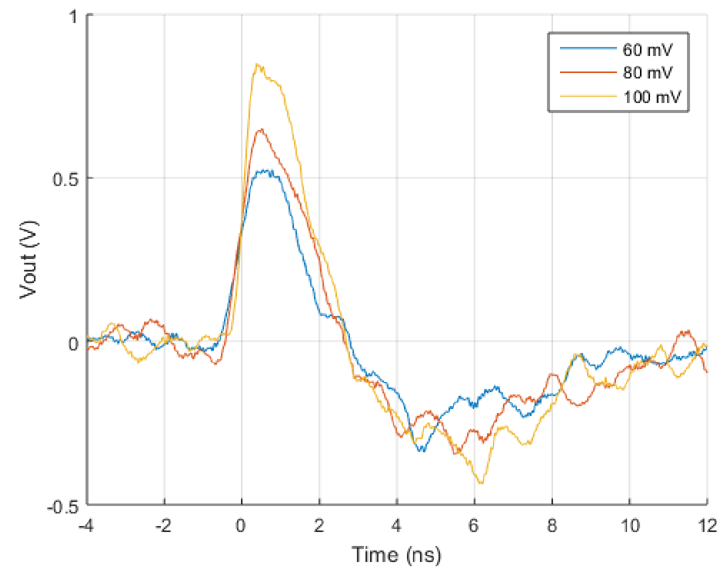
- Direct readout of 64 channels into an FPGA
- Brass flex circuits from < 1 – 40 K
- DC-coupled cryogenic amplifiers
- Copper flex circuits from 40 - 300 K
- Room temperature amplifiers and comparators
- FPGA-based time tagger
- Currently setting up SNSPD optical communication testbed

16-channel brass RF flex circuit

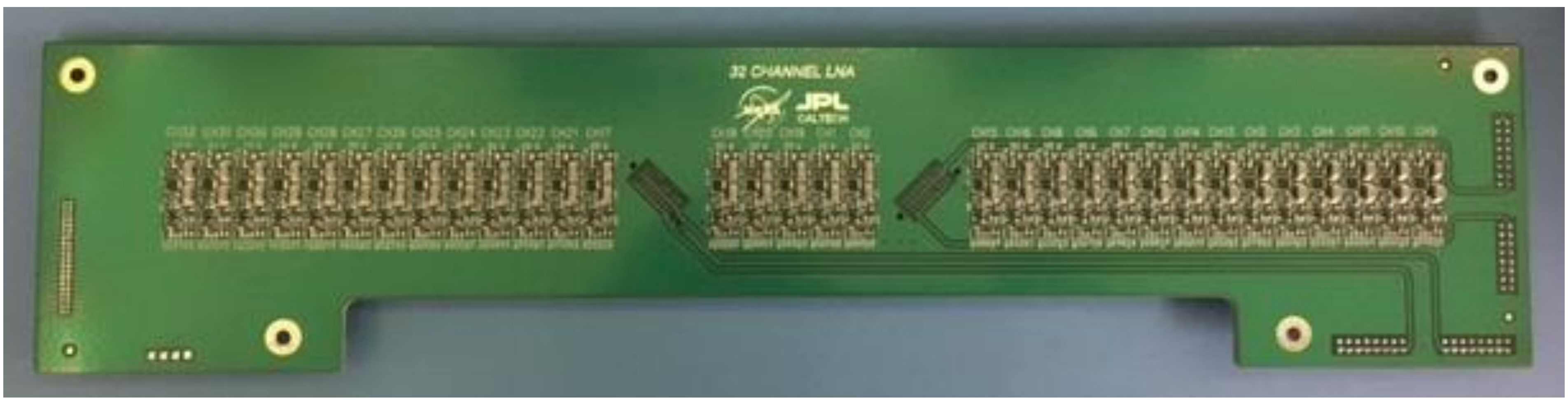


DC Coupled Cryogenic Amplifiers

- 2x 32-channel amplifier boards operated at 40 K
- 32 dB total gain
- Low-cost commercial cell phone components
- RFMD SGL-0622z cryogenic RF amplifier
- Broadcom ATF-35143 Psuedomorphic HEMT
- DC coupled with 50 ohm terminated input
- Detector bias added on amplifier board



SNSPD output pulses at different bias points

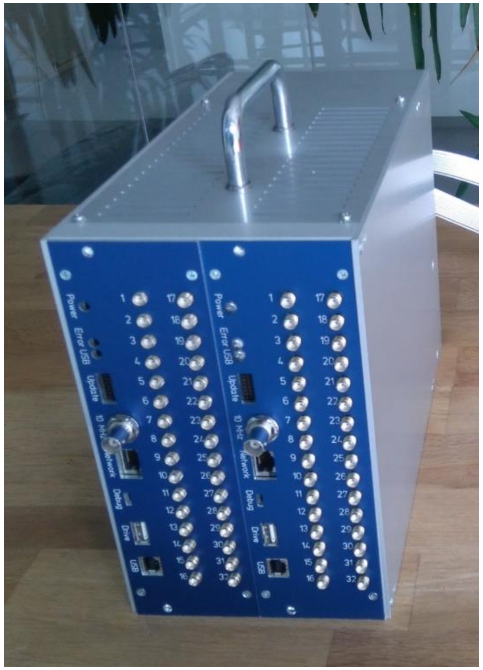


32-channel cryogenic amplifier board, operated at 40 K

Time to Digital Converter Development

- Asynchronous time tagging receiver approach
- Need to tag photon arrivals across 64 channels with ~150 ps resolution
- Need to stream data into receiver FPGA at ~ gigatag / second count rates
- Prototype TDC can fill 512 Mtag buffer at rates up to 600 Mtps w/ 166ps resolution
- Streaming TDCs are currently under development

Prototype 64-channel TDC (Voxtel)

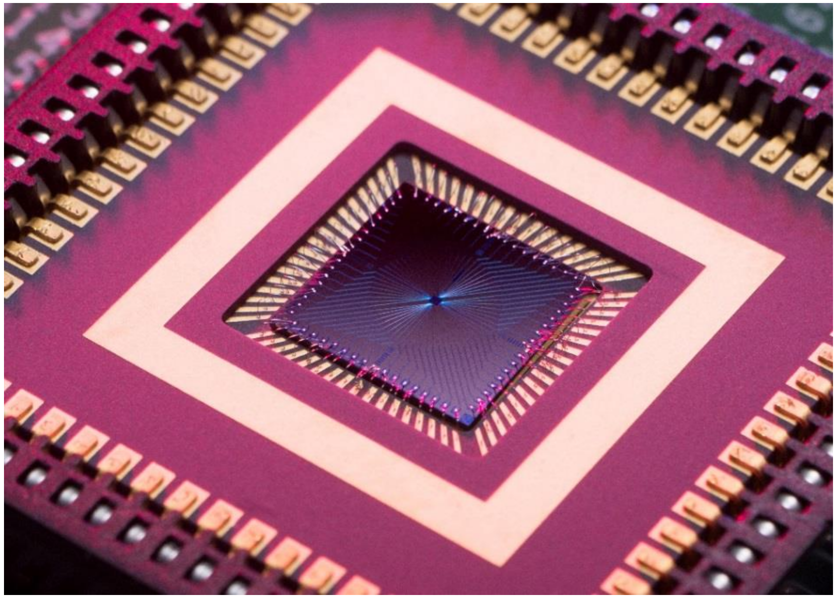


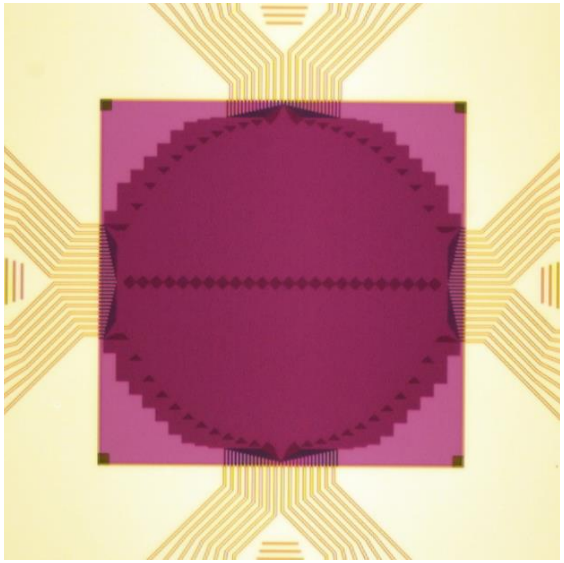
2x 32-channel comparator modules (UQD)

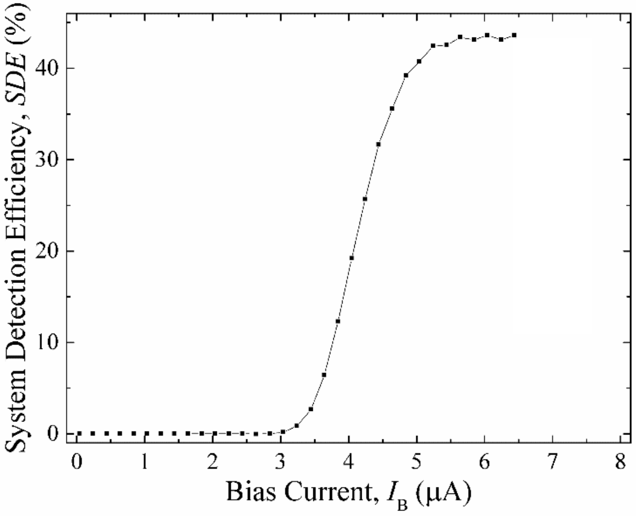
Summary

- The aggressive goals of the DSOC project have stimulated rapid advancement in SNSPD detectors for ground terminals

- 64-pixel WSi SNSPD arrays now have sufficient active area to couple efficiently to a 5-meter telescope and perform time-correlated single photon counting at gigacount per second count rates

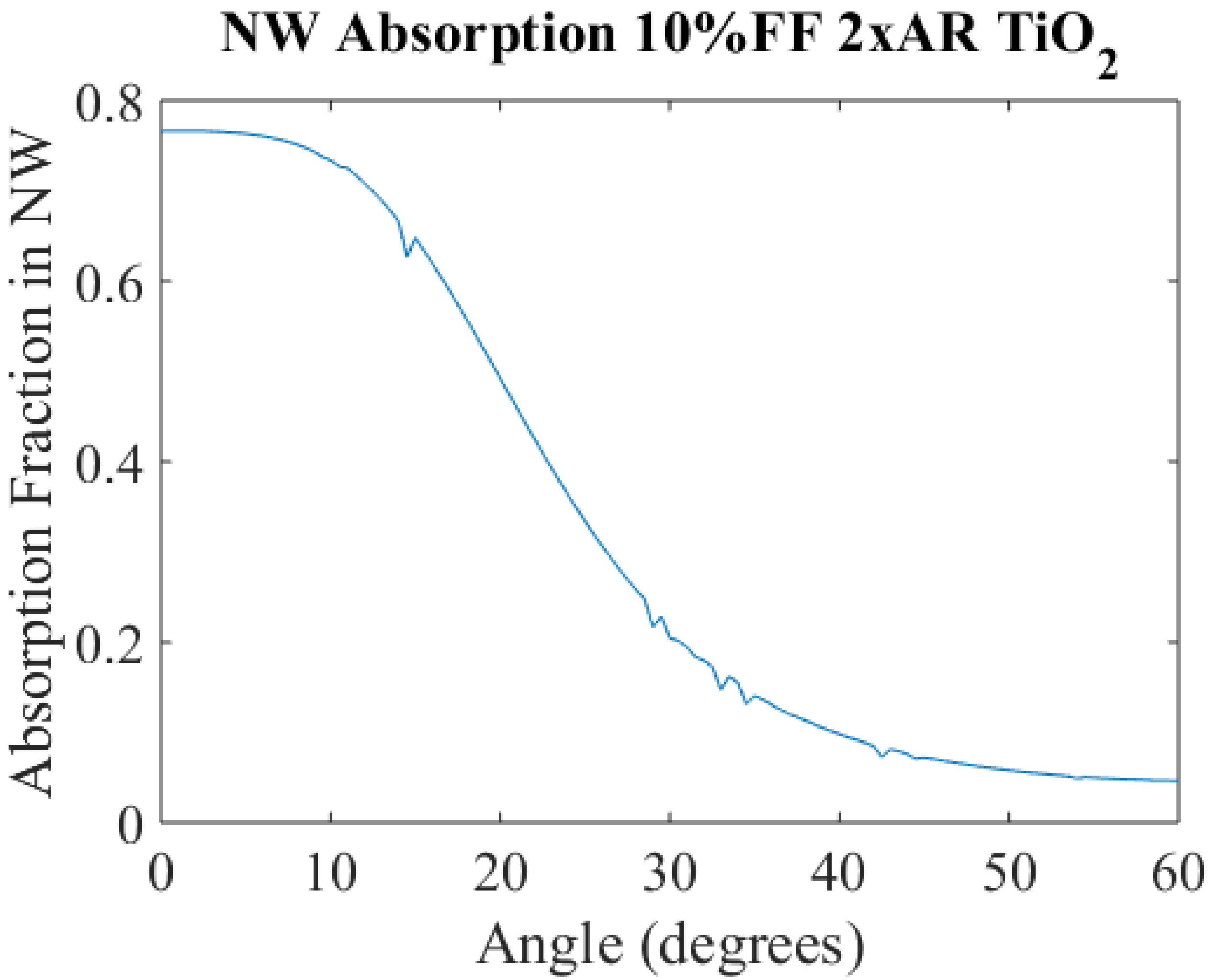




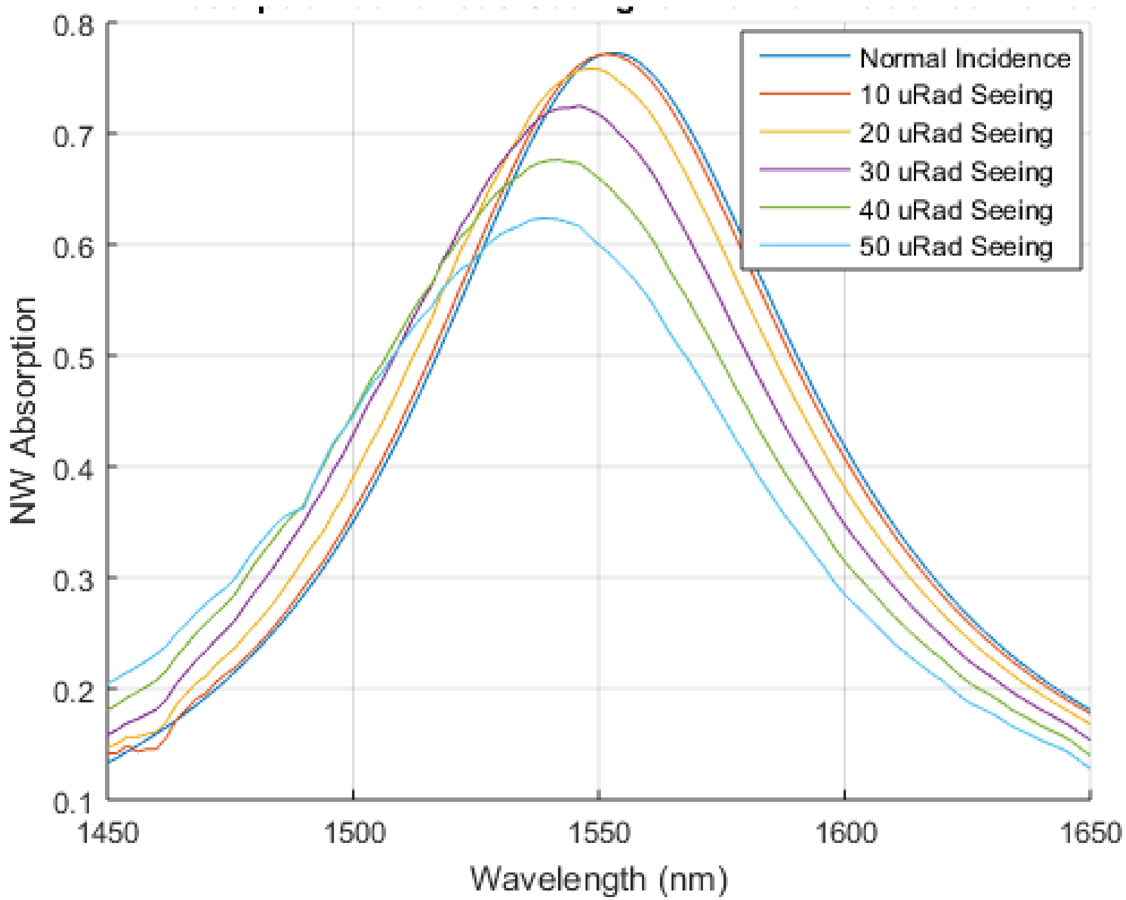


BACKUP

Angular Acceptance of Detector



Predicted Behavior for Realistic Beams



- Theoretical optical absorption in nanowires for TE polarization, optimized 2x TiO_2 AR coating
- RCWA theory includes diffraction effects, typically overestimates efficiency by ~5-7%
- Theory estimates 77% for perfectly collimated beam at 1550nm, 60% at 50 μrad seeing.